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Global validation of two-channel AVHRR aerosol optical thickness retrievals over the oceans

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Abstract

The paper presents validation results for the aerosol optical thickness derived by applying a two-channel retrieval algorithm to Advanced Very High Resolution Radiometer (AVHRR) radiance data. The satellite retrievals are compared with ship-borne sun-photometer results. The comparison of spatial and temporal statistics of the AVHRR results and the ship measurements shows a strong correlation. The satellite retrieval results obtained with the original algorithm for a wavelength of 0.55 μm are systematically higher than the sun-photometer measurements in the cases of low aerosol loads. The ensemble averaged satellite-retrieved optical thickness overestimates the ensemble averaged sun-photometer data by about 11% with a random error of about 0.04. Increasing the diffuse component of the ocean surface reflectance from 0.002 to 0.004 in the AVHRR algorithm produces a better match, with the ensemble-averaged AVHRR-retrieved optical thickness differing by only about 3.6% from the sun-photometer truth and having a small offset of 0.03.
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1. Introduction

The impact of aerosols on the global climate system through the direct and indirect radiative forcings is one of the major uncertainties in present climate studies [1–5]. The knowledge of aerosol physical and chemical properties is limited due to their high spatial heterogeneity and significant temporal variability.

A comprehensive long-term global aerosol climatology can be developed only by using satellite data. With its two-decade record and near global coverage, the Advanced Very High Resolution Radiometer (AVHRR) radiance dataset is a unique potential source of information about atmospheric aerosols. The papers by Mishchenko et al. [6,7] and Geogdzhayev et al. [8] outlined the methodology of inverting channel-1 and -2 AVHRR radiance data over the oceans, described a detailed analysis of the sensitivity of monthly averages of retrieved aerosols parameters (such as the aerosol optical thickness τ and the Ångström exponent A) to the assumptions made in various retrieval algorithms, and presented a global aerosol climatology for the period extending from July 1983 to September 2001.

As was discussed in detail in [6–8], the retrieval of τ and A from two-channel radiance data over the oceans requires several a priori assumptions in the retrieval algorithm, e.g., the form of the size distribution, the real and imaginary parts of the aerosol refractive index, the ocean reflectance model, etc. These assumptions together with all the uncertainties due to the satellite sensor itself and the measurement procedure generate errors in the retrieval results. Therefore, validation of the AVHRR aerosol product is very important and has been an essential aspect of our research. This effort has involved comparisons and consistency checks with other satellite, airborne, and ground-based datasets as suggested in [9–11]. Our product has been used in several inter-comparison studies of various satellite, ground-based, airborne, and model aerosol datasets (e.g., [7,9,12–14]). In general, the agreement of the satellite-derived monthly mean values of the aerosol optical thickness with the AERONET-derived [15–17] and the model-simulated results is good, and the most recent version of the retrieval algorithm [8] seems to provide a better agreement with the ground truth and the model aerosol data than the original one described by Mishchenko et al. [6]. The inter-comparison of Saharan dust aerosol optical thickness retrieved using aircraft-mounted pyranometers and our 2-channel AVHRR algorithms shows similar spatial distributions with less than ± 0.1 differences [9].

Many factors can contribute to discrepancies between satellite-derived results and ground-based or in situ measurements. These include space and time co-location problems, different cloud screening algorithms, imperfect instrumental calibration, occasional or frequent inadequacy of the ocean reflectance model used in the satellite retrieval algorithm, inconsistency between the fixed aerosol microphysical model used in the retrieval algorithm and the actual one at the specific location at the time of the measurement, and the atmospheric profiles implicit in each method. The discrepancies may also be associated with potentially higher surface albedos in coastal regions, where many ground-based instruments are located, compared to open ocean values assumed in the satellite retrieval algorithm.

In a recent paper, Smirnov et al. [10] summarized aerosol optical thickness data collected in maritime and coastal areas using sun-photometers mounted on scientific research vessels and/or cruise ships. This comprehensive survey of ship-borne measurements published over the last 30 years is a great asset for our validation effort since the ship data cover the same period of time as many of the AVHRR retrievals. Most of the sun-photometer data have been collected over open ocean areas, which allows us to disregard the possible coastline and shallow-water effects on the satellite retrievals.

2. Validation of AVHRR aerosol optical thickness retrievals

2.1. Methodology

The space–time collocation between satellite and sun-photometer observations is an important part of the validation process [18,19]. Many validation studies can be found in the literature (e.g., [11,18–25]), each with a different concept and procedure. Since a two-channel algorithm can retrieve only two aerosol parameters and must rely on globally fixed values of all other model parameters, and because the retrieval accuracy can be plagued by factors such as imperfect cloud screening and calibration uncertainties, it appears more appropriate to talk about the "calibration" of the algorithm in terms of minimizing the difference between the actual and the retrieved global and regional long-term averages of the aerosol properties.

The scarcity of the ship aerosol data and the limited number of cloud-free AVHRR pixels contained in the gridded ISCCP dataset [6,26] cause co-location problems that do not allow us to perform daily comparisons of satellite and sun-photometer results. However, even if such daily comparisons were possible, they would have little value because of the highly limited capabilities of a two-channel satellite retrieval algorithm [6–8], in which all model parameters but two must be globally fixed. Because of the limited performance of the satellite algorithm, the realistic goal of the two-channel AVHRR retrievals has been to provide accurate averages of the aerosol optical thickness and Ångström exponent over an extended period of time (e.g., a month) and over a relatively large area (e.g., $1^\circ \times 1^\circ$ or larger) [6–8]. Therefore, we have decided to adopt the following validation strategy:

1. To select only those sun-photometer measurement cycles that covered a significant spatial area and a significant period of time;
2. To average the ship sun-photometer optical-thickness results over each measurement period and, because of constant movements and mixing of air masses, to consider this average as being representative of the entire area covered by the ship over the measurement period (note that in a few cases we still include daily comparisons provided that the area covered by the ship and the amounts of both the shipborne and the satellite data accumulated over the course of a day are significant in order to compute meaningful averages);
3. To average the satellite optical thickness results over the same period of time and over the same area; and
4. To compare the sun-photometer and the satellite averages thus obtained.

This validation approach differs significantly from those previously published and based on daily comparisons, but appears to be more adequate given the inherent limitations of the AVHRR retrieval algorithm and the AVHRR and sun-photometer datasets.

We have not attempted to also validate the satellite Ångström-exponent results because the sun-photometer results are not available for all of the ship cruises selected (see Table 1), and because the definitions of the Ångström exponent were somewhat different in different studies.

2.2. Sun-photometer data

According to the recent review by Smirnov et al. [10], there are a total of 77 published data records of aerosol optical thickness measurements in maritime and coastal areas during the period from 1967

Table 1
Sun-photometer data selected for this study

Reference/dates[a]		Region	$\tau \pm \sigma_\tau$	$A \pm \sigma_A$	$N/H/D$
Volgin et al. [27]		Mediterranean Sea			
1.	08/13/86–08/28/86	33°N–40°N, 21°E– 27°E	0.20 ± 0.07	1.23 ± 0.19	—/25/11
2.	09/06/86–09/15/86	34°N–40°N, 12°E–29°E	0.17 ± 0.05	1.25 ± 0.35	—/21/9
		Pacific Ocean			
3.	11/01/85–11/04/85	10°–20°N, 145°E –158°E	0.05 ± 0.02	0.32 ± 0.34	—/7/4
4.	11/05/85–11/13/85	8°S–9°N, 159°E–175°E	0.08 ± 0.02	0.68 ± 0.49	—/5/4
5.	11/16/85–12/01/85	21°S–13°S, 166°W–172°E	0.06 ± 0.01	0.44 ± 0.36	—/24/15
6.	12/24/85–12/29/85	10°N–14°N, 124°E–140°E	0.07 ± 0.01	0.07 ± 0.17	—/6/4
Shifrin et al. [28]		Indian Ocean			
7.	11/17/83–11/18/83	11.6°N–12.4°, 45.8°E– 53.8°E	0.14 ± 0.04	0.16 ± 0.09	—/2/2
Sakerin et al. [29] and Korotaev et al. [31]		Atlantic Ocean			
8.	09/01/89–09/10/89	36.27°N–59.45°N, 9.77°W–2.85°E	0.20 ± 0.13	—	29/11/6
9.	09/22/89–10/03/89	33.34°N–41.96°N, 68.96°W–48.6°W	0.08 ± 0.07	0.94 ± 0.24	12/7/7
10.	10/04/89–10/11/89	17.02°N–28.24°N, 68.81°W–43.32°W	0.08 ± 0.03	1.53 ± 0.31	35/15/8
11.	10/12/89–10/26/89	6.23°N–15.19°N, 38.03°W–16.94°W	0.31 ± 0.19	0.62 ± 0.7	31/15/9
12.	11/17/89–12/04/89	2.02°N–16.42°N, 21.57°W–17.01°W	0.30 ± 0.10	0.67 ± 0.15	82/26/14
13.	12/05/89–12/14/89	20.96°N–31.28°N, 19.40°W–12.37°W	0.06 ± 0.03	0.69 ± 0.73	44/13/7
		Mediterranean Sea			
14.	12/15/89–12/20/89	35.18°N–40.22°N, 6.85°W–26.56°E	0.07 ± 0.05	0.1 ± 0.6	44/12/6
Wolgin et al. [30]		Atlantic Ocean			
15.	05/23/88–05/26/88	62.6°N–64°N, 3.3°W–4.7°E	0.16 ± 0.04	1.10 ± 0.09	—/5/3
16.	06/19/88–07/03/88	67.1°N–68.8°N, 2°W–0.4°W	0.11 ± 0.07	0.32 ± 0.10	—/2/2
Sakerin et al. [32]		Atlantic Ocean			
17.	07/04/91–08/03/91	24.99°N–32.97°N, 30.38°W–16.92°W	0.24 ± 0.17	0.7 ± 0.34	335/51/28
18.	08/04/91–08/09/91	33.36°N–39.76°N, 64.33°W–34.39°W	0.14 ± 0.03	1.02 ± 0.4	108/11/6
19.	08/18/91–09/08/91	38.28°N–40.3°N, 68.93°W–61.24°W	0.23 ± 0.27	0.99 ± 0.71	297/34/20
20.	09/19/91–09/26/91	38.32°N–41.02°N, 70.22°W–16.3°W	0.13 ± 0.08	0.23 ± 0.32	54/8/6
21.	09/09/91–09/18/91	36.76°N–39.29°N, 76.55°W–73.1°W	0.28 ± 0.20	1.41 ± 0.44	106/14/9
		Mediterranean Sea			
22.	09/29/91–09/30/91	37.23°N–37.25°N, 5.75°E–10.48°E	0.38	—	4/2/2
		Atlantic Ocean			
23.	05/01/94–05/22/94	22.82°N–28.14°N, 16.94°W–15.21°W	0.18 ± 0.16	0.84 ± 0.48	2750/32/19
Villevalde et al. [33]		Pacific Ocean			
24.	12/17/88–12/17/88	39.4°N–40°N, 170°E–170°E	0.13 ± 0.00	0.62 ± 0.07	—/2/1
25.	12/20/88–12/27/88	25°N–30°N, 154.7°E–180°E	0.09 ± 0.03	0.67 ± 0.32	—/8/6
26.	01/13/89–01/18/89	10.8°N–22.4°N, 133.8°E–156.2°E	0.14 ± 0.04	0.74 ± 0.24	—/12/6
27.	01/23/89–02/03/89	1.6°S–18.4°N, 174.9°E–180°E	0.15 ± 0.04	0.17 ± 0.18	—/15/9
28.	02/11/89–02/21/89	40°S–38.5°S, 157.6°E–179.9°E	0.13 ± 0.02	0.36 ± 0.04	—/3/3

Table 1 (*continued*)

Reference/dates[a]		Region	$\tau \pm \sigma_\tau$	$A \pm \sigma_A$	$N/H/D$
		Indian Ocean			
29.	03/13/89–03/16/89	23°S–9.1°S, 90°E–90°E	0.08 ± 0.02	0.08 ± 0.12	—/2/2
		Atlantic Ocean			
30.	05/14/89–05/26/89	58°N–67.3°N, 6.2°W–7°E	0.10 ± 0.02	1.42 ± 0.45	—/6/5
Sakerin et al. [34]		Atlantic Ocean			
31.	03/01/95–03/07/95	3.7°N–14.7°N, 20.47°W–13.09°W	0.41 ± 0.10	0.63 ± 0.4	1029/10/6
32.	03/08/95–04/04/95	1.65°S–0.29°N, 10.92°W–9.64°W	0.14 ± 0.08	0.76 ± 0.45	3090/34/19
33.	04/09/95–04/13/95	20.53°N–36.4°N,17.9°W–12.46°W	0.27 ± 0.11	0.56 ± 0.2	1245/8/4
34.	04/14/95–04/21/95	40.21°N–50.16°N,11.07°W–1.23°W	0.13 ± 0.07	0.86 ± 0.59	1097/13/7
Smirnov et al. [35]		Mediterranean Sea			
35.	12/14/89–12/21/89	37°N–40°N,1°W–13°E	0.04 ± 0.02	0.56 ± 0.29	—/4/3
36.	01/25/90–01/27/90	36°N–38°N,3°W–4°E	0.06 ± 0.03	1.09 ± 0.17	—/4/3
37.	08/25/91–08/30/91	36°N–38°N,2°E–25°E	0.23 ± 0.12	1.60 ± 0.53	—/6/4
		Black Sea			
38.	08/19/91–08/24/91	41°N–44°N,28°E–38°E	0.33 ± 0.06	1.72 ± 0.15	—/6/5
		Atlantic Ocean			
39.	09/02/91–09/23/91	37°N–48°N, 64°W–24°W	0.14 ± 0.07	0.96 ± 0.34	—/8/8
40.	12/29/89–01/19/90	23°N–27°N, 28°W–18°W	0.07 ± 0.03	0.34 ± 0.26	—/20/12
41.	10/03/91–10/18/91	21°N–28°N, 60°W–20°W	0.24 ± 0.04	0.68 ± 0.11	—/20/12
42.	01/21/90–01/24/90	28°N–35°N, 15°W–9°W	0.08 ± 0.02	0.93 ± 0.26	—/4/3
		Gibraltar Area			
43.	10/26/91–10/27/91	35°N–36°N, 13°W–9°W	0.21 ± 0.05	1.39 ± 0.29	—/3/2
Smirnov et al. [36]		Baltic Sea			
44.	05/16/84–05/18/84	56.1°N–56.1°N, 11.8°E–19.1°E	0.46 ± 0.01	1.16 ± 0.02	—/2/2
		Atlantic Ocean			
45.	05/20/84–06/06/84	60.5°N–65°N, 4.8°W–2.7°W	0.20 ± 0.08	1.21 ± 0.33	—/4/4
		Baltic Sea			
46.	07/06/84–07/07/84	59°N–59.3°N, 21.1°E–23.5°E	0.09 ± 0.01	0.95 ± 0.11	—/2/2
Kabanov et al. [37]		Atlantic Ocean			
47.	08/25/96–08/26/96	44.03°N–44.03°N, 63.55°W–63.55°W	0.13 ± 0.11	1.25 ± 0.18	25/2/2
48.	08/27/96–09/13/96	29.15°N–41.24°N, 58.24°W–21.44°W	0.08 ± 0.04	0.59 ± 0.42	2622/35/18
49.	09/14/96–09/15/96	44.16°N–46.7°N, 15.61°W–10.32°W	0.09 ± 0.02	0.48 ± 0.04	210/1/2
		English Channel			
50.	09/16/96–09/17/96	49.55°N–51.83°N, 3.7°W–2.76°E	0.10 ± 0.02	0.95 ± 0.24	288/4/2
Moorthy et al. [38]		Indian Ocean			
51.	01/07/96–01/22/96	5°S–8.83°N, 60°E–69°E	0.19 ± 0.10 (500 nm)	—	—/15/13
Moulin et al. [39]		Atlantic Ocean			
52.	09/14/91–09/29/91	15.5°N–27.7°N, 31.15°W–17.9°W	0.46 ± 0.31	0.32 ± 0.14	—/—/13

Table 1 (*continued*)

Reference/dates[a]		Region	$\tau \pm \sigma_\tau$	$A \pm \sigma_A$	$N/H/D$
Kuśmierczyk-Michulec [40]		Baltic Sea			
53.	07/02/97–07/15/97	54°N–58.5°N, 11°E–21°E	0.21 ± 0.09	1.11 ± 0.28	145/—/12
Smirnov et al. [41]		Atlantic Ocean			
54.	07/08/96–07/08/96	34.93°N–37.3°N, 69.95°W–67.34°W	0.29 ± 0.07	1.80 ± 0.07	24/—/1
55.	07/18/96–07/18/96	32.37°N–32.78°N, 64.87°W–64.58°W	0.06 ± 0.01	0.79 ± 0.09	8/—/1
56.	07/26/96–07/26/96	36.74°N–38.17°N, 70.89°W–68.48°W	0.16 ± 0.04	0.88 ± 0.21	12/—/1
57.	07/27/96–07/27/96	35.82°N–38.24°N, 71.09°W–68.3°W	0.25 ± 0.13	1.68 ± 0.14	28/—/1
58.	07/08/96–07/27/96	32.37°N–40.76°N, 74.01°W–64.57°W	0.19 ± 0.12	1.24 ± 0.48	130/—/7

[a] Read xx/xx/xx as mm/dd/yy. τ and σ_τ are the mean value and the standard deviation of the aerosol optical thickness at the wavelength 0.55 μm, A and σ_A are the mean value and the standard deviation of the aerosol Ångström exponent, N is the number of datasets, H is the number of half day averages, and D is the number of observation days.

to 2001. Not all of the data summarized by Smirnov et al. can be used to validate the results of the AVHRR retrievals. Indeed, 33 records had been collected before July 1983, i.e., before the current AVHRR aerosol climatology starts. Furthermore, for some sun-photometer datasets collected after July 1983, the measurement accuracy is unknown [10] and/or the data points are too few in order to compute a meaningful average.

Table 1 summarizes the ship measurements selected for this validation study. The instruments, the measurement technique, and the measurement errors have been documented and can be found in the corresponding references as well as in the papers by Kabanov and Sakerin [42] and Sakerin and Kabanov [43]. It has been estimated that the optical thickness errors do not exceed 0.02 in the visible spectral range. This accuracy is quite adequate for the purpose of validating the AVHRR optical thickness retrievals.

2.3. Validation results

Results of the comparison of the aerosol optical thickness at a wavelength of $\lambda = 0.55$ μm retrieved from the AVHRR data, τ^{SAT}, and that measured by ship-borne sun-photometers, τ^{SP}, for 58 case studies are summarized in Fig. 1. Each data point is numbered according to the corresponding dataset in Table 1. The figure clearly reveals the spatial distribution pattern of the aerosol optical thickness described by Smirnov et al. [10]. Specifically, the atmosphere over the Pacific Ocean is more transparent than over the Atlantic Ocean, inland seas, and coastal zones. There is generally a good agreement between the satellite retrievals and the ship data. One can see that over the Pacific Ocean, the retrieved τ^{SAT} values are higher than the ship-measured τ^{SP}. Aerosol optical thickness over the Atlantic Ocean shows significant variability, but the systematic bias of τ^{SAT} relative to τ^{SP} is somewhat smaller compared to that over the Pacific Ocean. However, we again see a slight overestimation in τ^{SAT}. Since there are very little aerosol data for the other areas except perhaps the Mediterranean Sea, the comparison results are less conclusive.

Performing a linear regression analysis yields the relation $\tau^{SAT} = 0.047 + 0.836\tau^{SP}$ with a high correlation coefficient R of 0.90 and a standard deviation σ of 0.04. However, the ensemble-averaged $\langle\tau^{SAT}\rangle$ is 0.188, which is 11.2% higher than $\langle\tau^{SP}\rangle = 0.169$. The systematic errors of the retrieval algorithm for low (τ^{SP} close to 0), average ($\tau^{SP} \approx \langle\tau^{SAT}\rangle$), and high ($\tau^{SP} \approx 1$) aerosol loads are found to be close to 0.047,

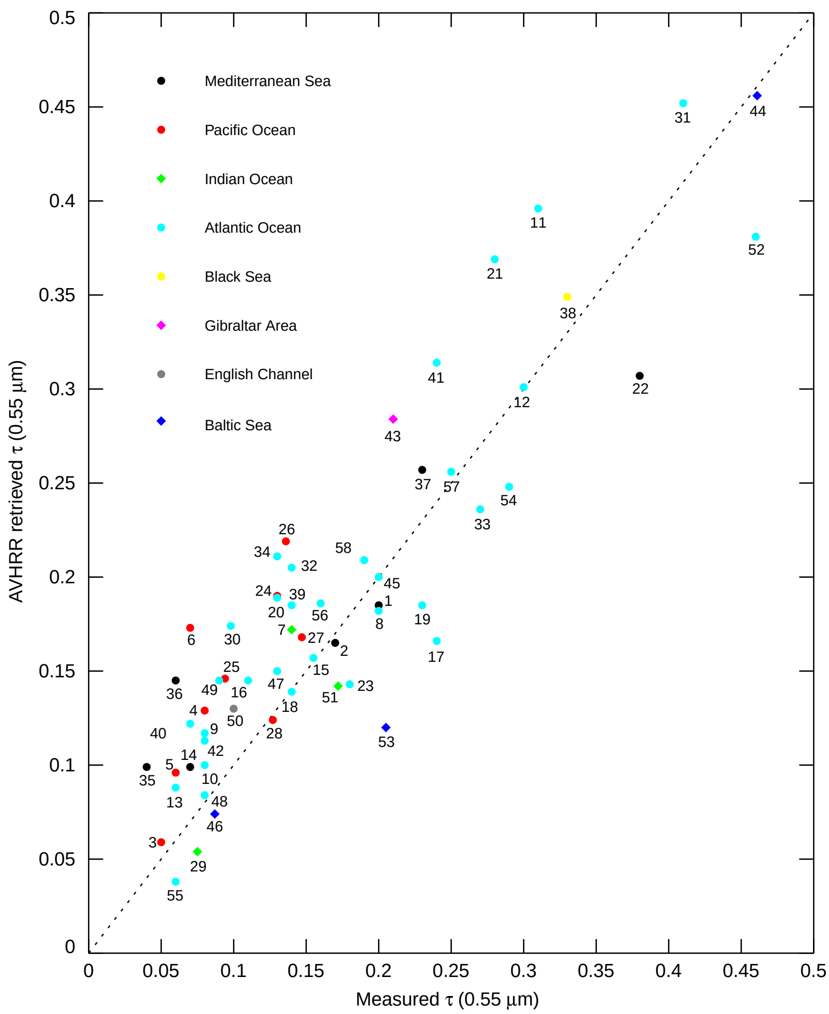

Fig. 1. AVHRR-retrieved aerosol optical thickness τ^{SAT} versus ship measurements τ^{SP} at $\lambda = 0.55$ µm. Different regions are represented by different colors and symbols. The number near each data point corresponds to the respective ship-borne dataset shown in Table 1.

0.019, and −0.117, respectively. This is comparable to the values reported by Zhao et al. [11] after the cloud and wind effects had been minimized in their retrievals. These values indicate that the satellite retrievals tend to overestimate the optical thickness in cases of low aerosol loads and underestimate it otherwise. A similar pattern has also been reported by Myhre et al. [14] in their comparison study of aerosol optical thickness over the oceans for five different retrieval algorithms and four different satellite instruments.

The non-unity slope in the regression may be associated with insufficient accuracy of the model assumptions in the satellite retrieval algorithm vis-à-vis the actual conditions at the sites of the ship measurements. Due to the significant aerosol and ocean heterogeneity on the global and regional scales, this problem cannot be readily solved with the current retrieval algorithm, which relies on a globally uniform

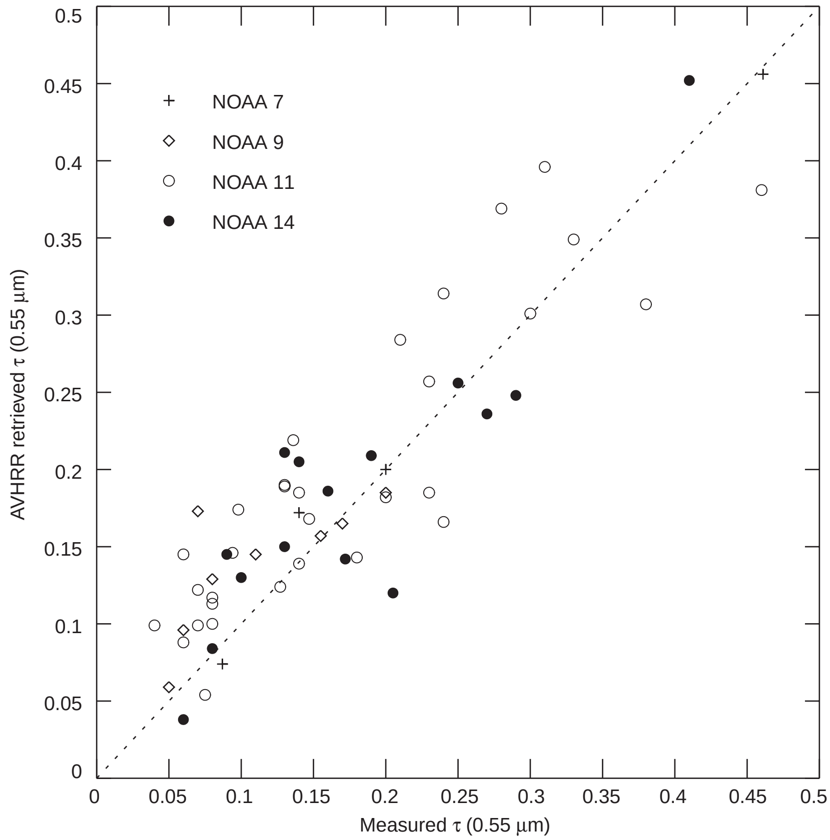

Fig. 2. τ^{SAT} versus τ^{SP} for the AVHRR instruments on board of NOAA-7, -9, -11, and -14 satellites.

atmosphere–ocean model. A possible improvement is to adopt regional models which take into account, e.g., the stronger absorptivity of soot and dust-like particles (e.g., [44]) and the nonsphericity of mineral aerosols (e.g., [45–47]). This is a great challenge and will be the subject of our future research. A nonzero intercept may result from effects such as sensor calibration errors and subpixel cloud contamination [19].

In order to improve the agreement between the satellite retrievals and the ship data, we can try to reduce the positive intercept. An overestimation of the optical thickness by the satellite retrieval algorithm in cases of low aerosol loads can result from either a systematic underestimation of the ocean surface reflectance and/or a systematic radiance calibration error, namely an error in the offset (deep space count) value. In order to distinguish between the two potential causes, we repeated the comparisons using data from the individual AVHRR instruments (those on NOAA-7, -9, -11, and -14), each with its own calibration coefficients. The results are shown in Fig. 2. It is clear that no obvious satellite-specific discrepancy can be discerned. We are thus inclined to believe that the likely cause of the optical thickness overestimation by the satellite retrieval algorithm is too low a value of the ocean surface reflectance used in the algorithm.

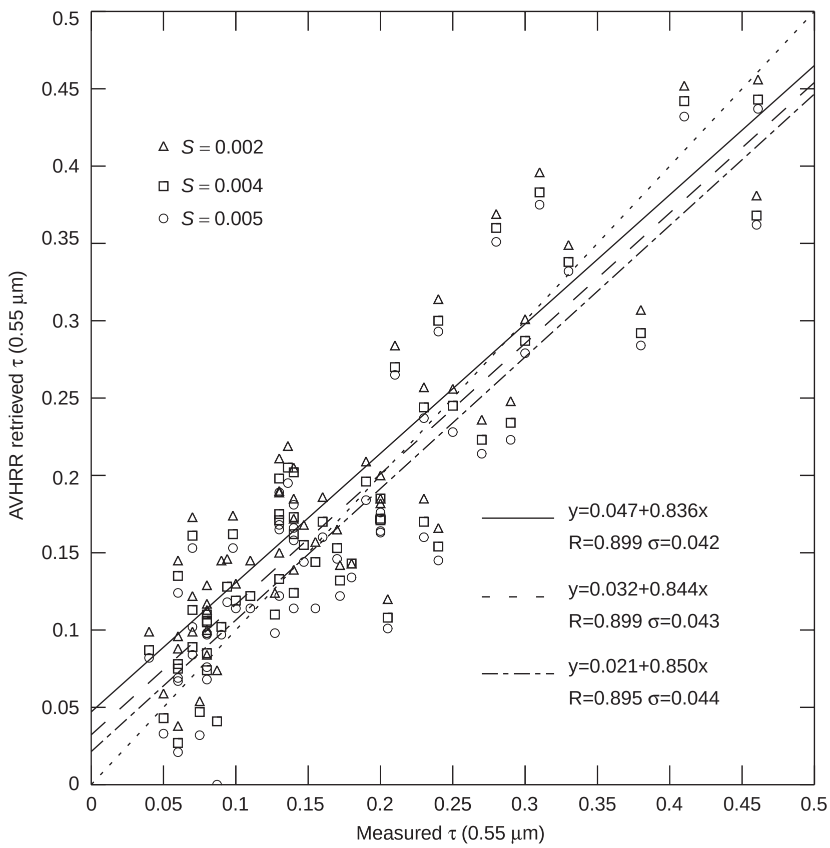

Fig. 3. Comparison of τ^{SAT} and τ^{SP} at $\lambda = 0.55$ μm for three increasing values of the diffuse component of the ocean surface reflectance $S = 0.002$, 0.004, and 0.005 and the corresponding linear regression lines. The dotted line depicts the 1:1 relationship.

Fig. 3 shows τ^{SAT} versus τ^{SP} at $\lambda = 0.55$ μm and the corresponding linear regressions derived using three increasing values of the Lambertian (diffuse) component of the ocean surface reflectance S in the satellite algorithm. The dotted line represents the 1:1 relationship. The detailed statistics are summarized in Table 2 . Note that the current two-channel retrieval algorithm uses the value $S = 0.002$. Although choosing $S = 0.005$ appears to minimize the offset, one should take into account that the satellite retrievals are extremely sensitive to a particular selection of the surface reflectance in cases of low aerosol loads. For example, one may notice that one satellite retrieval falls to zero if $S = 0.005$. Overall, the value $S = 0.004$ appears to be a good choice in terms of minimizing the differences between the actual and the retrieved aerosol optical thicknesses, with the ensemble average of τ^{SAT} being different from that of τ^{SP} by only 3.6%. Linear regression of τ^{SAT} versus τ^{SP} produces a good match, $\tau^{SAT} = 0.032 + 0.844\tau^{SP}$, with a high correlation coefficient of 0.9 and a small standard error of 0.04. This is rather encouraging, especially if one takes into consideration that AVHRR was not specially designed for aerosol retrievals and is less advanced and well calibrated than instruments such as the MODerate Resolution Imaging Spectrometer (MODIS) [22,24,25] and the Multiangle Imaging SpectroRadiometer (MISR) [48].

Table 2
Statistics of the comparison of τ^{SAT} and τ^{SP} for three increasing values of the diffuse component of the ocean surface reflectance $S = 0.002$, 0.004, and 0.005[a]

S	a	b	R	Mean		Systematic errors			σ
				τ^{SAT}	τ^{SP}	Low	Average	High	
0.002	0.047	0.836	0.899	0.188	0.169	0.047	0.019	−0.117	0.042
0.004	0.032	0.844	0.899	0.175	0.169	0.032	0.006	−0.124	0.043
0.005	0.021	0.850	0.895	0.165	0.169	0.021	−0.004	−0.129	0.044

[a]The systematic errors are defined as ensemble averages $\langle \tau^{SAT} - \tau^{SP} \rangle$ computed for the cases of low, average, and high aerosol loads. R is the coefficient of correlation between τ^{SAT} and τ^{SP}. The parameters a, b, and σ are the intercept, slope, and standard deviation, respectively, of the linear regression line.

3. Discussion and conclusions

We have used ship-borne aerosol data with well characterized accuracy to validate our global two-channel AVHRR retrievals. In general, the satellite-derived aerosol optical thickness values are in good agreement with the sun-photometer data. We have found that by adjusting the diffuse component of the ocean surface reflectance from 0.002 to 0.004, we are able to reduce the positive offset from 0.047 down to 0.032 (Table 2). The positive bias in the AVHRR-retrieved τ^{SAT} compared to τ^{SP} in cases of average aerosol loads was reduced from 0.019 (11.2% relative to τ^{SP}) to 0.006 (3.6% relative to τ^{SP}).

The remaining systematic errors in cases of low aerosol loads and the random errors may be attributed to imperfect cloud screening (residual clouds may still exist within the “cloud-free” pixels as determined by the retrieval algorithm), calibration uncertainties, instrumental noise, and/or measurement instability. We expect that the sensor-related error sources will have a lesser effect on aerosol retrieval results from the more advanced satellite instruments. Our future research will focus on comparisons of the AVHRR-derived aerosol properties over the oceans with these new satellite data products.

The source of the apparent systematic errors in cases of large aerosol loads is less obvious. For example, Zhao et al. [11] have shown that such errors can be reduced by increasing the imaginary part of the aerosol refractive index Im(m). However, one can argue that a good agreement with a limited ground-based or in situ dataset does not guarantee the global applicability of the satellite-retrieved product. The study by Mishchenko et al. [7] indicates that the currently adopted value $\mathrm{Im}(m) = 0.003$ can be a reasonable choice for the area in the vicinity of Sable Island [49] since it provides close agreement between the AVHRR-retrieved and in situ measured values of the single-scattering albedo and the Ångström exponent. However, this value may not be ideal in other areas, e.g., those affected by biomass burning. Particle nonsphericity may also contribute to the discrepancy between the satellite retrievals and the ship measurements in the cases of significant aerosol loads since high aerosol optical thickness values are often due to dust aerosols, which are inherently nonspherical.

Another direction of our current research is to compare the satellite retrievals with AERONET observations. The results obtained so far are similar to those reported by Zhao et al. [11] and will be the subject of a separate publication.

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